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Cross-sectional atomic force microscopy of ZnSe-based laser diodes

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Abstract. Cleaved facets of ZnBeMgSe-based lasers with different design of active region have been studied by means of the cross-sectional atomic force and lateral (friction) force microscopy (AFM and LFM). A difference in friction coefficients has been successfully exploited to image basic layers of the laser diodes. The Be-containing cladding layers and the waveguide area are revealed as regions of lower friction as compared to a GaAs substrate. Elastic strains accumulated at the layer boundaries are displayed via nanometer-high steps and undulations forming in the morphology of the cleaved facets. A remarkable reduction of the elastic strain in the active region containing a (Zn, Cd)Se quantum well has been found for the laser with the specially designed alternately-strained superlattice in the waveguide.

Introduction

The cleavage of an ideally perfect crystal is expected to be atomically plain and to exhibit no structure [1]. Contrary to that an epitaxial semiconductor heterostructure is obviously not the ideal crystal and usually consists of alternatively strained heterolayers. Recent cross-sectional atomic force microscopy (AFM) studies of such heterostructures have revealed an existence on cleaved facets of the nanometer-high topographic singularities placed along the interfaces [2–4]. A possible mechanism of the relief formation on the cleavages of strain compensated heterostructures is an elastic relaxation of the surface due to strain variations in underlaying layers [2]. For strained heterostructures another scenario was also proposed, including cleavage crack deviation at the interface between two materials with different fracture toughness due to occurrence of a plastic deformation by the glide of misfit dislocations [3]. Thus, AFM topography data may be used to extract a valuable information on the structural properties of the constituent layers of the heterostructure. The AFM data may be completed if lateral force microscopy (LFM) mode measuring frictional forces is used. The friction force may vary between different materials and utilization of the LFM mode permit one to distinguish different semiconductor layers on cleaved facets [3, 4].

We applied cross-sectional AFM for the characterization of the cleavages of ZnSe-based laser diode heterostructures, which still remain the main candidates for fabrication of a commercial injection laser for the green (490–550 nm) spectral region [5]. However, for the successful development of those devices it is still necessary to increase an onset energy of appearance and development of the extended defects in ZnSe-based materials and to suppress their propagation and multiplication in a laser device [6]. A promising approach to solve these problems is to employ Be-containing compounds. The beryllium-based chalcogenides (e.g. BeMgZnSe) are expected to increase significantly the covalent component of the bond, hence “hardening” the material [7, 8]. In addition, an efficient gradual strain redistribution in the active region of the II–VI lasers is proposed by incorporation of

specially designed alternately-strained superlattice (AS SL) waveguide, lattice-matched to a GaAs substrate [9].

Experimental results and discussion

We have investigated three BeMgZnSe/ZnCdSe-based laser heterostructures with different active region design. The first one of a conventional type involves a $0.2\ \mu\text{m}$ $\text{Be}_{0.03}\text{Zn}_{0.97}\text{Se}$ bulk waveguide centered with a $4\ \text{nm}$ - $\text{Zn}_{0.63}\text{Cd}_{0.37}\text{Se}$ quantum well (QW) and surrounded by $1\ \mu\text{m}$ thick widebandgap n- and p-BeMgZnSe cladding layers doped with iodine and nitrogen, respectively. In the second structure the bulk waveguide is exchanged by a $(1\ \text{nm}-\text{Be}_{0.05}\text{Zn}_{0.95}\text{Se}/1.5\ \text{nm}-\text{ZnSe})_{82}$ AS SL lattice-matched to GaAs as a whole. Contrary to the second structure, the third one contains a $2.8\ \text{ML}-\text{CdSe}/10\ \text{nm}-\text{ZnSe}$ fractional monolayer (FM) nanostructure instead of the conventional QW. The growth conditions and composition control for the structures have been reported elsewhere [7, 8, 10, 11].

The cross-sections of laser heterostructures were prepared by cleavage in air. The samples thinned to approximately $200\ \mu\text{m}$ were placed on the polished brass plate face down. The cleavage was initiated by pressing the cutter on the GaAs substrate along the $\langle 110 \rangle$ direction. The freshly cleaved samples were studied in air by AFM (P-4 SPM, NT-MDT) operating in contact mode. Commercial Si triangular cantilevers were used with a normal elastic constant of $0.68\ \text{N/m}$ and with the radius of curvature of the tip less than $40\ \text{nm}$. LFM images were obtained when scanning in the direction nearly perpendicular to the longest axis of the cantilever. To minimize the cross-talk between normal and lateral deflections of the cantilever a low scanning speed of about $1\ \mu\text{m/s}$ was employed.

Fig. 1 presents cross-sectional AFM data and a schematic band energy diagram for the laser heterostructure with the CdSe/ZnSe FM active region. AFM topography image of laser cleavage presented in Fig. 1(b) reveals two singularities on the cleavage surface: (i) $0.2\ \text{nm}$ -high ridge and (ii) $0.5\ \text{nm}$ -high step, running parallel to the heterostructure interfaces identified by their distances from the top cleavage edge (not included in the image). The ridge is placed at the center of the waveguide area (W), while the step coincides with the II-VI/GaAs interface. The linear dimensions of the ridge and step may be better seen in the AFM profile (Fig. 1(c) taken along A–A line in the AFM topography image.

The LFM image taken simultaneously with AFM topography from the same cleavage area is shown in Fig. 1(d). Here the darker grey tone corresponds to smaller lateral deflection of the cantilever and, hence, to smaller friction force. The observed contrast arises mainly from the lateral variations in friction between the tip and underlying layers, which was confirmed by a reversal of the image grey contrast when the scanning direction was reversed [12]. The friction force is characterized by the value of the current arising in the deflection detector of the SPM device when cantilever twists due to lateral forces. Variation of the friction force (in the units of the deflection detector current) in the direction normal to the interfaces is shown in Fig. 1(e). The presented plot is averaged over the whole studied cleavage area. The mean friction force on GaAs is taken as a zero level. The detectable differences in friction, when crossing the laser interfaces, are found, which provides explicit visualization of the basic layers of the laser structure in good agreement with the laser diagram in Fig. 1(a). Similar surface morphology and friction force behaviour have been found for the cleavages of the rest two laser structures. However, the conventional type laser demonstrates a much higher step of $1.7\ \text{nm}$ at the QW position instead of the low $0.2\ \text{nm}$ ridge.

Before discussing the obtained topography data, it is interesting to note that the friction force on the II–VI layers, demonstrated by the cleavages of all the studied laser structures, is

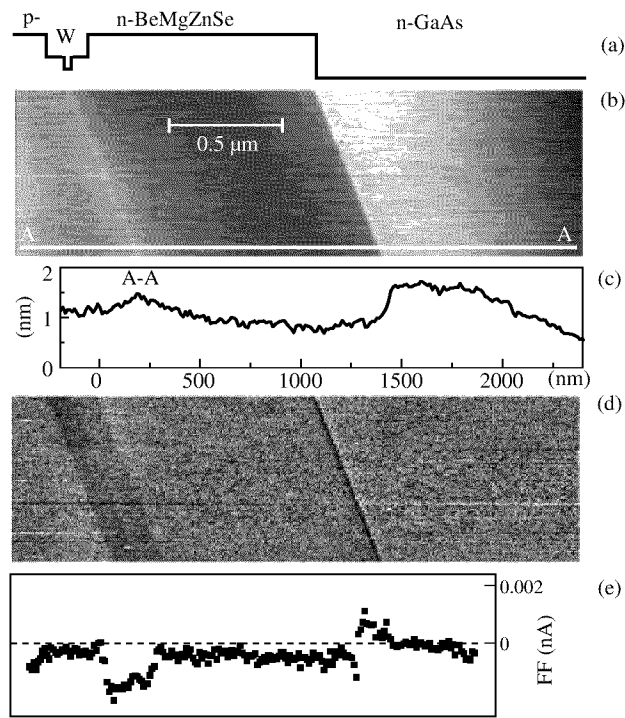


Fig. 1. (a) the conduction band energy diagram for the laser structure of the third type; (b) AFM topography image of laser cleavage; (c) the AFM profile taken along A–A line in the AFM topography image; (d) the LFM image taken in parallel with AFM topography image from the same cleavage area; (e) graph of the averaged friction force signal across the interfaces.

smaller than that on the GaAs substrate. In general, one could expect the contrary relation, since ZnSe is considerably softer than GaAs [3]. One should probably take into account different structural properties of oxides formed at ZnSe and GaAs, which may enlarge or even reverse somehow the contrast. This problem certainly needs a separate study. However, the comparative study of S-contained and Be-contained II–VI heterostructures shows that the Be incorporation, even at the level of several percents, increases the hardness of the II–VI epilayers [13]. The additional confirmation is provided by Fig. 1(d) and 1(e), where the area of ZnBeSe waveguide is characterized by the lowest friction force. An introduction of softening Mg to the cladding layers enhances the friction on these layers, but the presence of the Be still remains the friction force lower than that at the GaAs substrate.

The character of singularities occurring on the cleavages of the laser structures allows one to elucidate directly the strain distribution in the active region of the structures. Two studied QW laser structures have nearly the same lattice mismatch 2% between the waveguides and 4 nm-QWs. On the other hand, a total energy of deformation related to the 2.6 ML CdSe insertion (7% of lattice mismatch) is of the order of that accumulated by the thicker QWs of the lower Cd content. For the laser of conventional type, the 1.7 nm high step has been found at the interface between waveguide and the QW. Earlier it was found that the step height increases with the mismatch value [3], and thus, with the total energy of deformation. The step may appear to reduce the elastic strains at the QW/waveguide interface in the case

when the release of strain energy is larger than an increase in free surface energy. For both laser structures with AS SL waveguide we did not find any high step, but only a small undulation in waveguide area of the cleavage. This observation leads us to the conclusion about a considerable reduction of the total energy of deformation in the active region due to redistribution or “smoothing” of the elastic strain over the whole waveguide. It means that AS SL play a special role of the strain redistributing spring. By the way, the resulting diminished strains in the waveguide region can initiate an expansion of the SL waveguide area over cleavage surface, which is revealed as the ridge in the AFM image in Fig. 1(b) and (c).

It is interesting to note that the height of the observed surface singularities did not change notably along the interfaces, but the singularity shape did. In the case of step, we observed an abrupt change in the step side orientation. A ridge structure could transform into a double ditch. We believe that these local transformations in the cleavage morphology are related to some structural defects at the interfaces.

Conclusion

Our work demonstrates possibilities of AFM and LFM studies of the heterostructure cleavages as a powerful alternatives to conventional epilayer thickness determination and strain detection techniques, like SEM and TEM.

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